PZT Active Frequency Based Wind Blade Fatigue to Failure Testing Results for Various Blade Designs

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14. ABSTRACT
This paper summarizes NASA PZT Health Monitoring System results previously reported for 9 meter blade Fatigue loading to failure conducted at The National Renewable Energy Lab Wind blade testing facility results using the on the CX-100, TX-100 and BSDS designs. A collaborative effort between Sandia National Laboratories (SNL) and NASA KSC has been performed to evaluate the viability of a NASA Developed PZT Piezoelectric sensor/actuator for structural health monitoring (SHM) of Wind turbine blades. The innovation behind the NASA developed sensors in the combination of signal data processing with the development of a unique sensor/actuator consisting of piezoelectric materials in a thin and highly sensitive configuration. This paper summarizes previous NASA PZT system testing and includes results of the Fatigue testing of a 9 Meter Wind blade fatigue test referred to as the Sensor Blade which was based on the CX-100 design. This configuration had internal instrumentation/video and consisted of an internal manufacturing known defect. The defect provided an opportunity to demonstrate the PZT Health monitoring performance.

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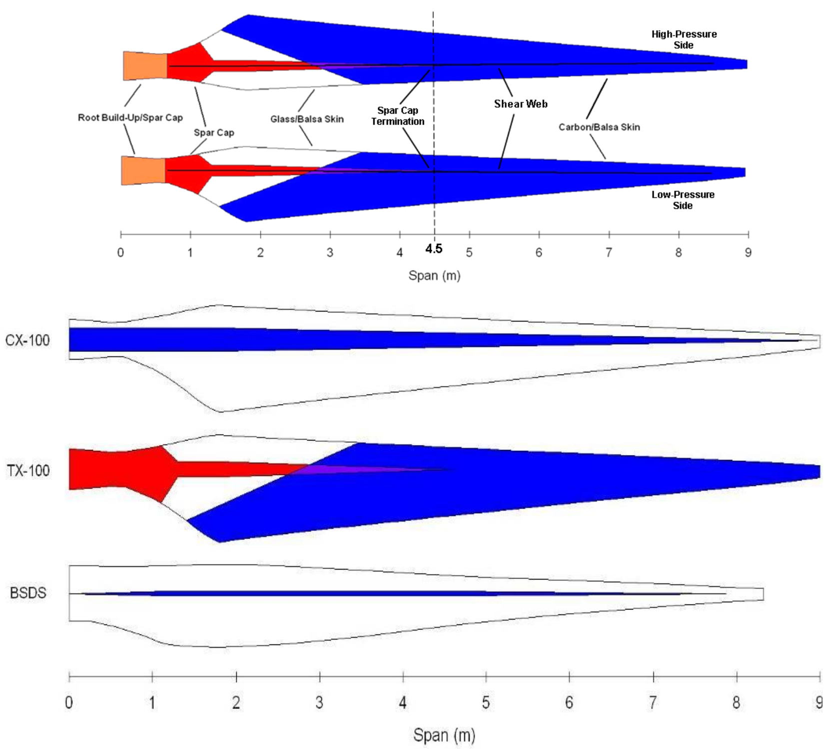
Abstract:

This paper summarizes NASA PZT Health Monitoring System results previously reported for 9 meter blade Fatigue loading to failure conducted at The National Renewable Energy Lab Wind blade testing facility results using the on the CX-100, TX-100 and BSDS designs. A collaborative effort between Sandia National Laboratories (SNL) and NASA KSC has been performed to evaluate the viability of a NASA Developed PZT Piezoelectric sensor/actuator for structural health monitoring (SHM) of Wind turbine blades. The innovation behind the NASA developed sensors in the combination of signal data processing with the development of a unique sensor/actuator consisting of piezoelectric materials in a thin and highly sensitive configuration. This paper summarizes previous NASA PZT system testing and includes results of the Fatigue testing of a 9 Meter Wind blade fatigue test referred to as the Sensor Blade which was based on the CX-100 design. This configuration had internal instrumentation/video and consisted of an internal manufacturing known defect. The defect provided an opportunity to demonstrate the PZT Health monitoring performance.

CX-100[1] / TX-100[2] and BSDS[3] Historical PZT Health Monitoring Results: A joint test between the Wind Energy Technology Department at SNL and NASA KSC to evaluate a NASA developed PZT sensor/actuator has been conducted on a fatigue test of four designs of 9-meter composite wind turbine blades. The CX-100 and the TX-100 (also referred to as 3X-100) blades, are nearly identical, Both blades consisted of a carbon spar cap and a fiberglass shell and shear web design The CX-100 and 3X-100 Two were heavily instrumented with traditional foil strain gauges and the NASA PZT sensor. A fatigue to failure test was performed independently on both blades at the NWTC lab testing facility. During the test, data from both the foil strain gauges and the NASA PZT's was collected. The NASA PZT sensors are being evaluated to determine their feasibility for SHM of a composite structure.

Figure 1 inner detail for TX-100 / CX-100, BSDS 9M Blades



-CX-100

- Carbon spar cap
- Glass skin and shear web

– **TX-100**

- Carbon triax in skin for bend-twist coupling
- Constant spar cap thickness

– **BSDS (Blade System Design Study)**

- Flat back airfoils
- Carbon spar cap
- Slenderized platform
- Large scale architecture
- Highly efficient structural design [4]

Figure 2 shows the Fatigue Test loading for the CX-100 and TX-100 blades (Free blade ends were cut off to aid in control of loading)

Table 1: Loads and loading intervals for 3X-100 and CX-100 blade tests.

Cycle Range	Minimum Load (lb)	Maximum Load (lb)
$0–1.0×10^6$	281	2810
$1.0×10^6–1.5×10^6$	309	3091
$1.5×10^6–2.0×10^7$	337	3372

Figure 3 TX-100 Visual cracking near mid span several meters away from nearest PZT sensor[5]

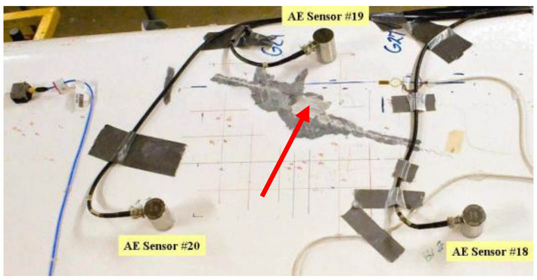


Figure 4 shows the TX-100 FRF transmissibility (averaged variances) of the PZT system for sensor 1 to sensor 3 are variable during early loading but drop drastically starting around 1,100,000 cycles indicating major fault development.

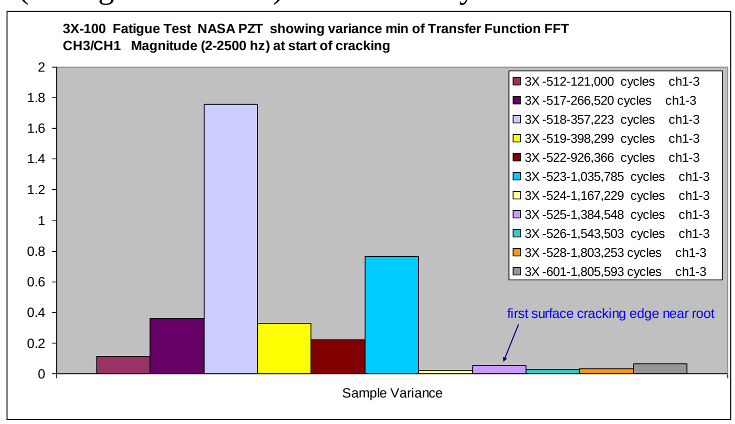


Figure 5 CX-100 FRF transmissibility (averaged areas) of the PZT system for sensor1 to sensor3

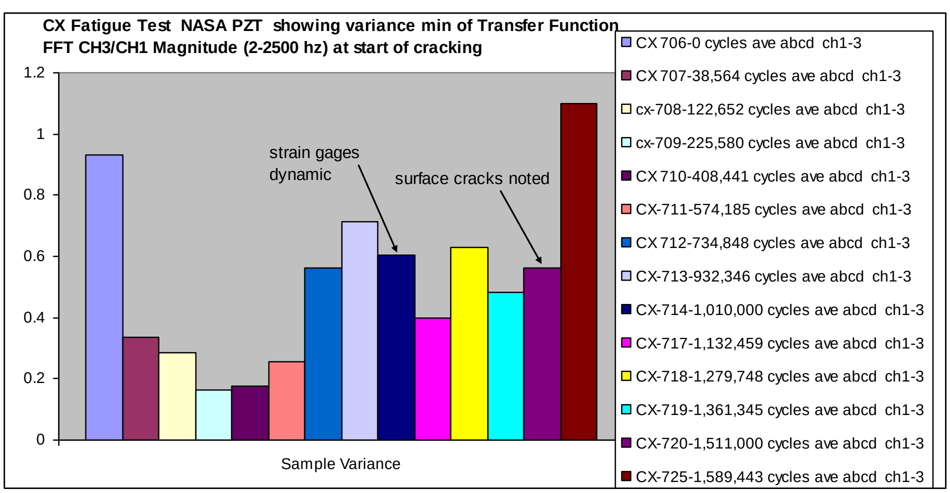


Figure 5 above shows the CX-100 FRF transmissibility (averaged areas) of the PZT system for sensor1 to sensor3 are decreasing during early loading but increases around 700,000 cycles starting indicating major fault development.

BSDS Historical results:

The loads were applied to a saddle located at a station 5.0 meters from the base of the blade. Loading frequencies started at 1.5 Hz and had to be slowly decreased as the load was increased. The final load frequency was 0.65 Hz. The loading started with 1.0 million cycles in the flap orientation. The test was then stopped and the blade reoriented to allow edge loading. Another 1.0 million cycles were applied. Little apparent damage was detected and the blade was again reoriented back to the flap mode. Ten percent increases in the load were then applied, first at half million cycle increments and then at one quarter million cycle increments. This was continued until the blade finally failed at 418 % of the initial load. The blade showed no surface cracks until Load Block 13 at 5.8M cycles. A large crack which failed the blade was noticed at LB15.

Figure 6 BSDS Fatigue Cracks

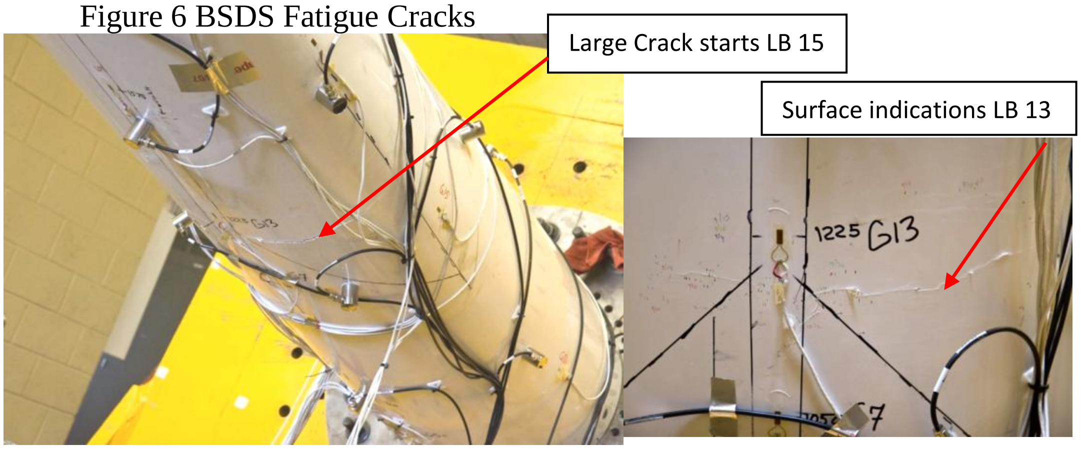
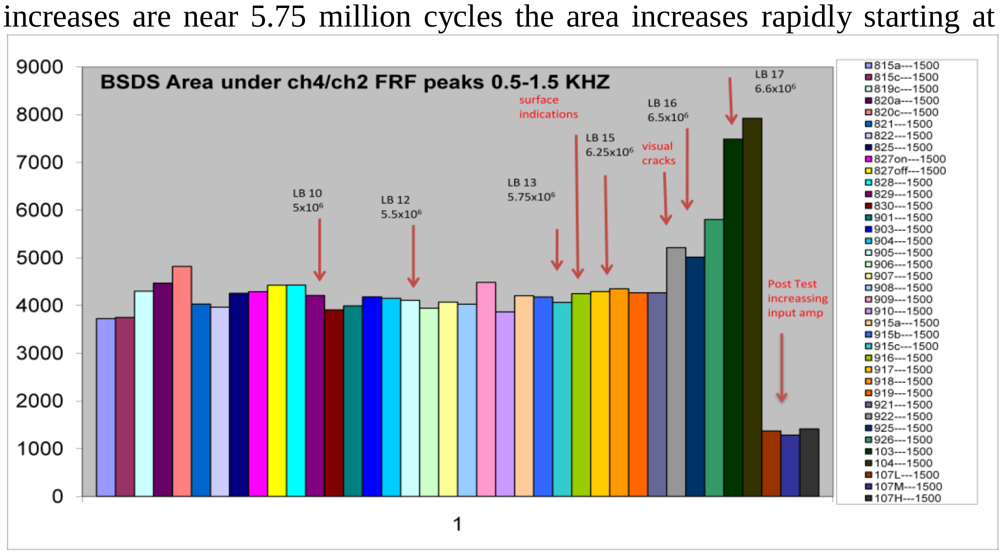


Figure 7 showing BSDS FRF averaged areas for sensor 2 to sensor 4 over the load cycles first increases are near 5.75 million cycles the area increases rapidly starting at 6.5 million cycles.



Summary of Completed Fatigue Blade Testing:

Table 2 Shown below are the summarized test results for the PZT NASA Health Monitoring Technology

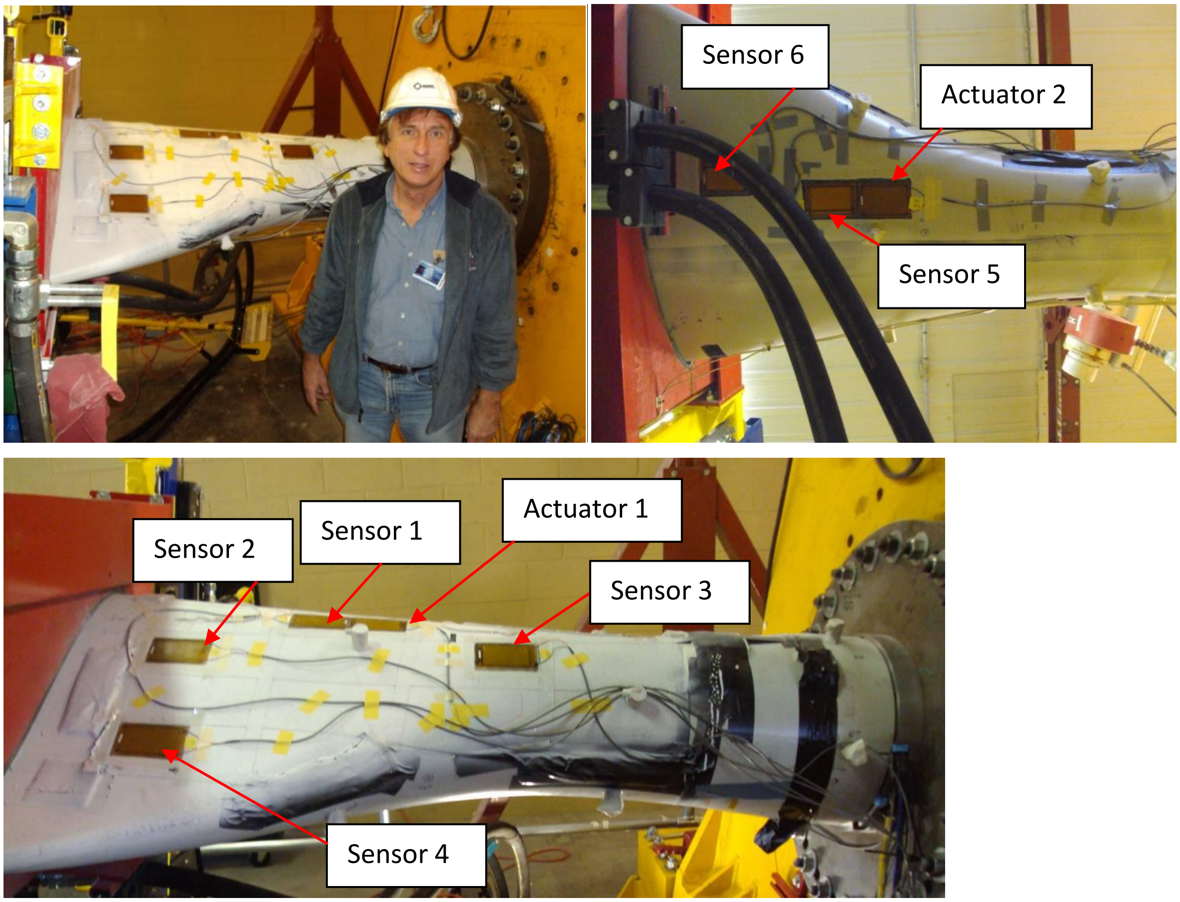
Blade description	Number Load Cycles to first/final visual evidence	Description of failure	NASA PZT first detection load cycles
TX (3X) -100	700k/1,800k	Low pressure mid blade (4.5 M) surface cracking	1,100k
CX-100	1,400k/ 1,600k	Low pressure surface cracking near root	700k
BSDS	6,000k/6,600k	Low pressure surface cracking near 1.2 M from root	5,750k

Sensor Blade Fatigue Testing:

Sandia National Laboratories designed and conducted an experiment where a variety of new structural testing methods were built into a wind turbine blade during its construction. This 9 meter blade was then flown on a Sandia wind turbine near Amarillo TX. After flight testing, the blade was transported to the National Wind Laboratory near Boulder CO where it underwent a nondestructive static load test and a destructive fatigue test. This section describes the fatigue test results in regards to the NASA PZT Health Monitoring system. While there were other monitoring systems including Acoustic Emission At this writing, neither the results of the other test methods nor information on their designs were available to the author.

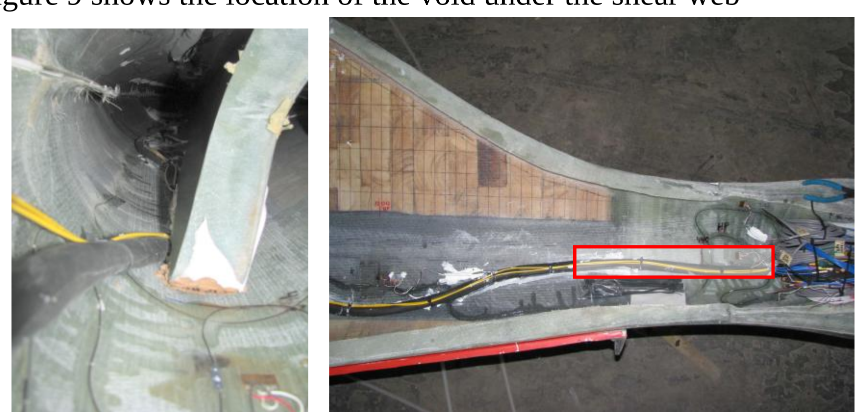
Fatigue testing is described as follows: The blade was mounted in a horizontal position with its base firmly attached to a rigid structure. It was inverted with the compression side facing down. The excitation was at its fundamental resonant frequency of about 1.85 Hz, applied by hydraulically driven oscillating weights mounted on a saddle near the 1600 mm station from the root. The blade was weighted near the tip so that the maximum vertical travel of the blade was the normal rest load on the blade and the minimum vertical position corresponded to a maximum load on the blade. The amplitude of the oscillating weights determined the applied load. The blade was fatigued for about 1,000 K cycles at the starting load. The test schedule then had the load increased by 10% every 100 K cycles. The test is divided into ten Load Blocks. These methods are very similar to the previous TX-100, CX-100 and BSDS testing already reported.[6]

Figure 8 Layout of PZT sensors and actuators



The defect shown below was unintentional manufactured into the Sensor Blade; one of the sensor cable bundles, inside the blade, were accidentally sandwiched between the high-pressure skin and the spar cap, in a critical area in the root section of the blade. However the defect provided an opportunity to evaluate Health monitoring system response

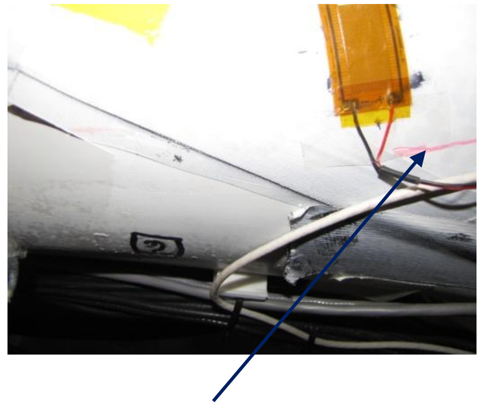
Figure 9 shows the location of the void under the shear web



the red rectangle shows the problem area located between 0.4-0.8

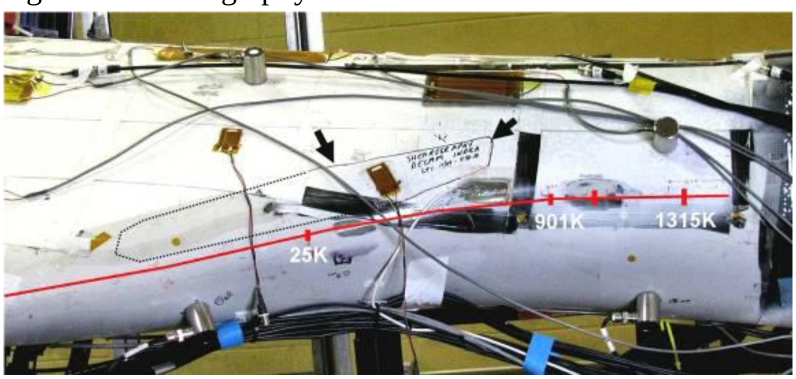
meters under the shear web.

Figure 10 Results of Sensor Blade Fatigue Test



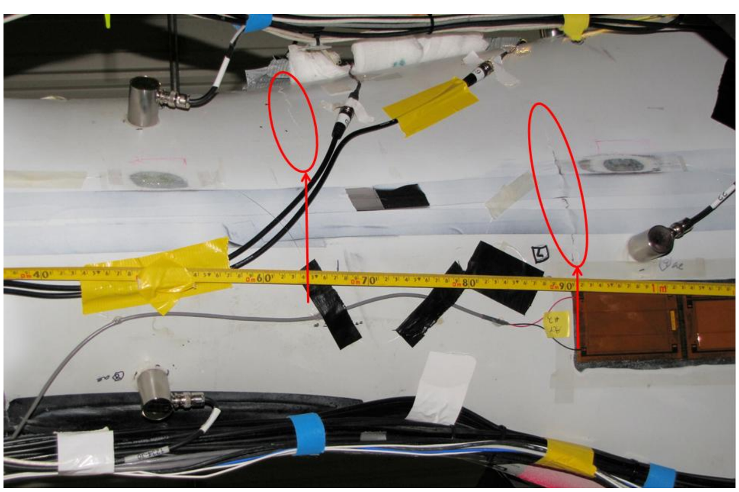
Early surface cracks noticed at 25k load cycles near internal shear web bonding cable manufacturing defect Figure showing manufacturing cause delamination[7]

Figure 11 Stereography indicated a void area related to manufacturing defect close to sensor 3



The post test inspection shows the crack surface break-through location adjacent to the aft edge Below the delamination (black are marked on the surface, arrow) at 25K cycles. The crack (red line) propagated both towards the root and tip as shown with marks showing the extent at 901K and 1315K cycles. The dotted lines show suspected extent of the delamination covered by instrumentation protective covering.[8]

Figure 12 Sensor Blade Post test failure area



The Low Pressure down side of Blade Post test failure area shown by red circle on right which occurred suddenly Circle on left shows secondary cracking stemming from initial cracks which did not fail blade.[9]

The early edge surface cracks were likely caused by the manufacturing defect, delimitation occurred below the surface very close to PZT sensor 3 and it showed a much higher output voltage reflecting the high strain. After this the fatigue loads were taken up by other structure with blade failure occurring finally through the shear web showing up on the opposite side. See below for post test photographs:

Results of Sensor Blade Fatigue testing using the NASA PZT Heath Monitoring System:

The PZT FRF transmissibility (averaged areas) Plots of magnitude vs. number of load cycles in thousnads (K) data distributed in frequency (Hz) blocks of 1-100, 100-500, 500-1500, 1500-2500, 2500-5000. See Figures 13-16 below:

Figure 13 Sensor Blade PZT System FRF (averaged) Transmissibility from sensor 1 (near Actuator 1) to sensor 2 periodical during NWTC Fatigue loading to failure

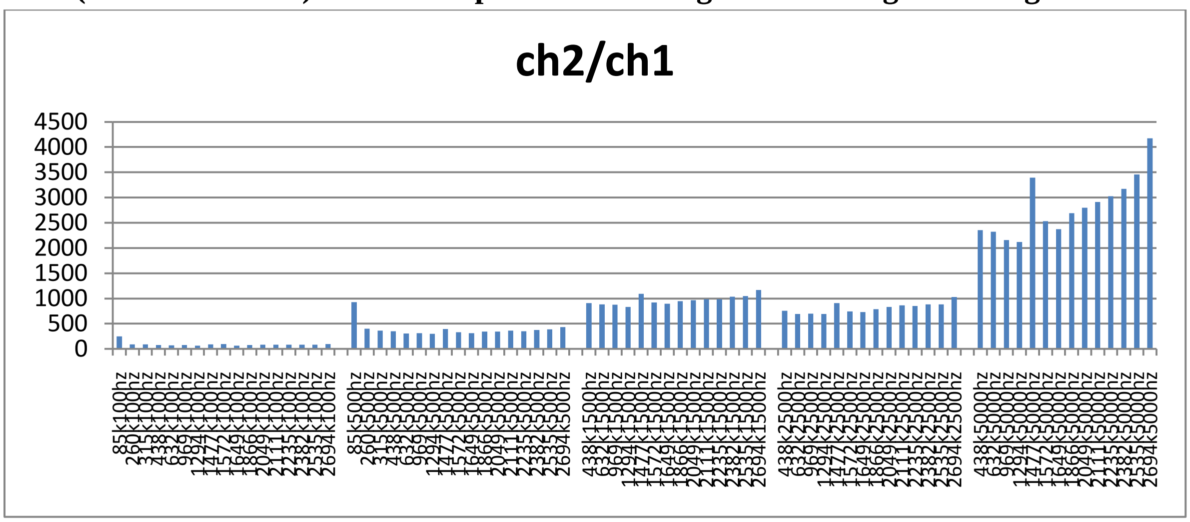


Figure 14 Sensor Blade PZT System FRF (averaged) Transmissibility from sensor 1 (near Actuator 1) to sensor 3 (around void) periodical during NWTC Fatigue loading to failure

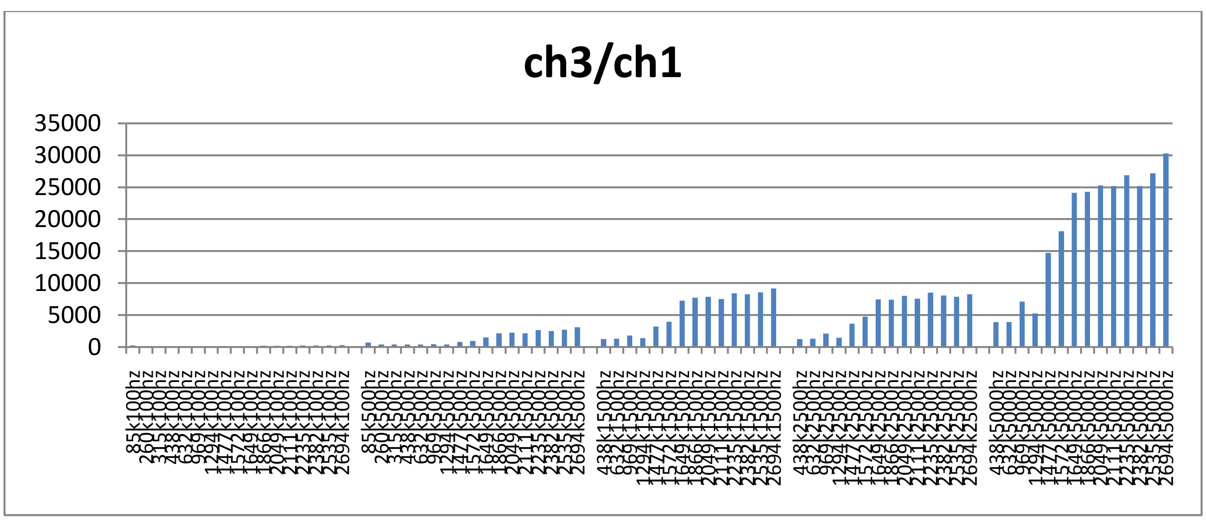


Figure 15 Sensor Blade PZT System FRF (averaged) Transmissibility from sensor 1 (near Actuator 1) to sensor 4 periodical during NWTC Fatigue loading to failure

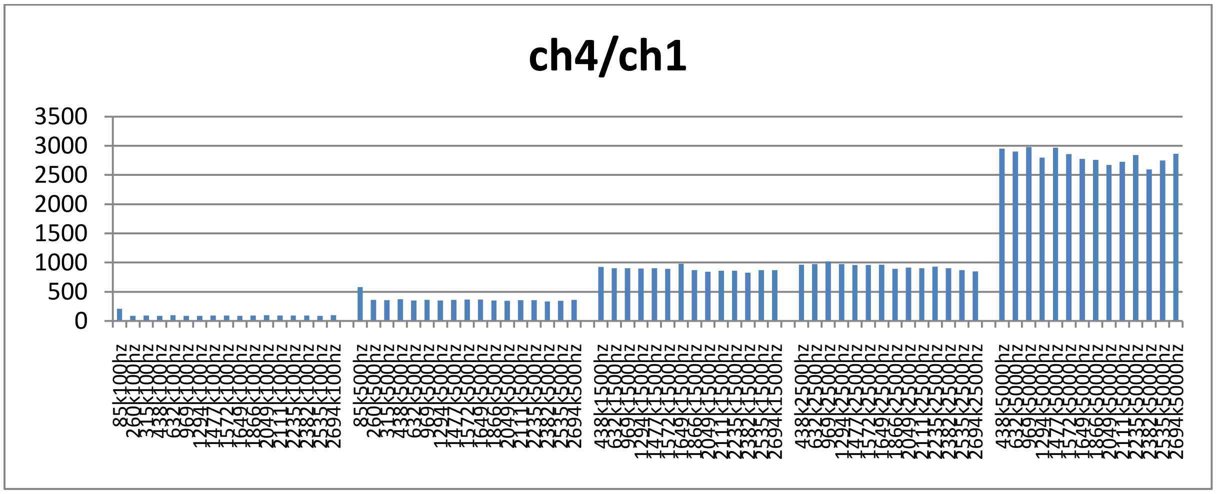
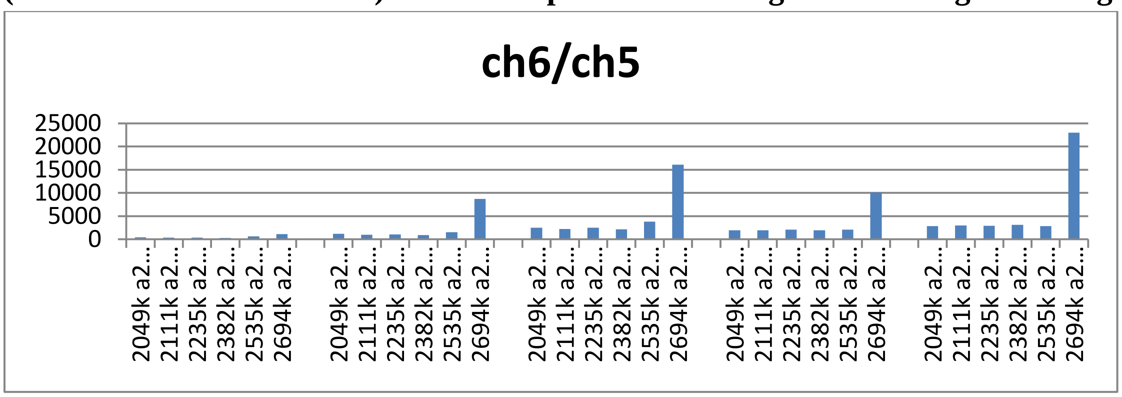


Figure 16 Sensor Blade PZT System FRF (averaged) Transmissibility from sensor 5 (near Actuator 2 down side) to sensor 6 periodical during NWTC Fatigue loading to failure



The PZT FRF transmissibility (averaged areas) Plots of magnitude vs. number of load cycles in thousands (K) data over frequencies 1-5000 (Hz). See Figures 17-20 below:

Figure 17 Sensor Blade PZT System FRF (averaged) Transmissibility from sensor 1 (near Actuator 1) to sensor 2 periodical overall frequency range 1-5000 Hz

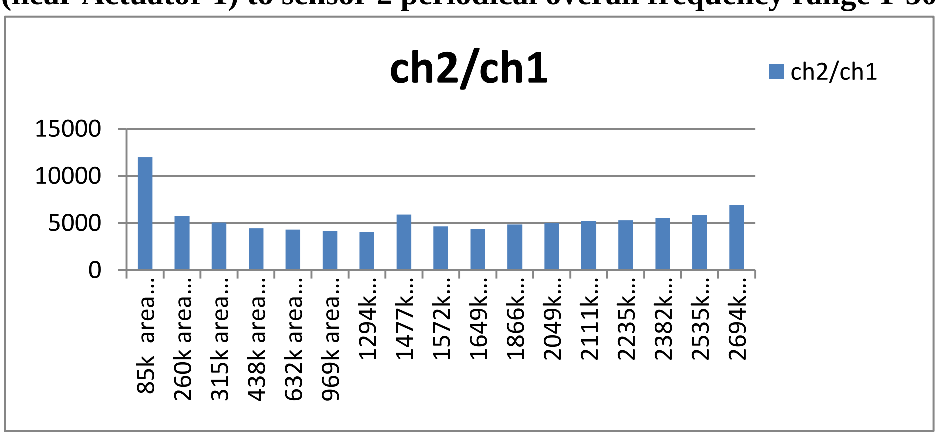


Figure 18 Sensor Blade PZT System FRF (averaged) Transmissibility from sensor 1 (near Actuator 1) to sensor 3 (around void) periodical overall frequency range 1-5000 Hz

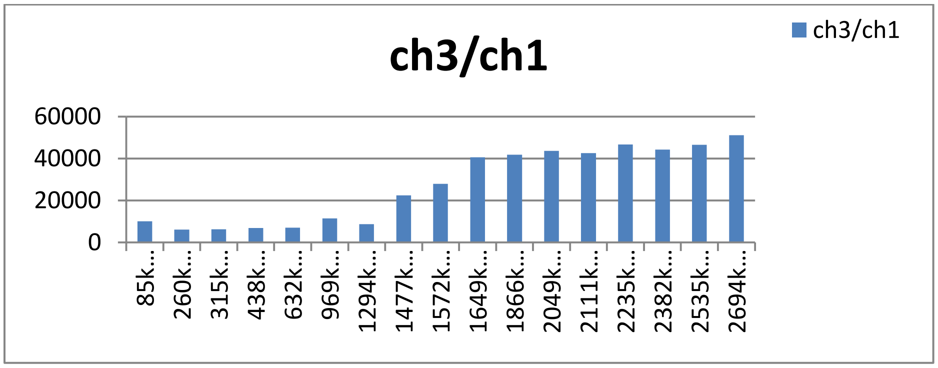


Figure 19 Sensor Blade PZT System FRF (averaged) Transmissibility from sensor 1 (near Actuator 1) to sensor 4 periodical overall frequency range 1-5000 Hz

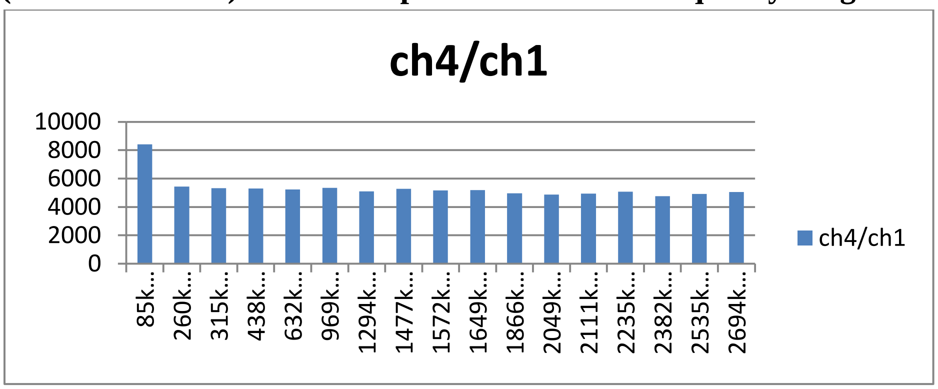
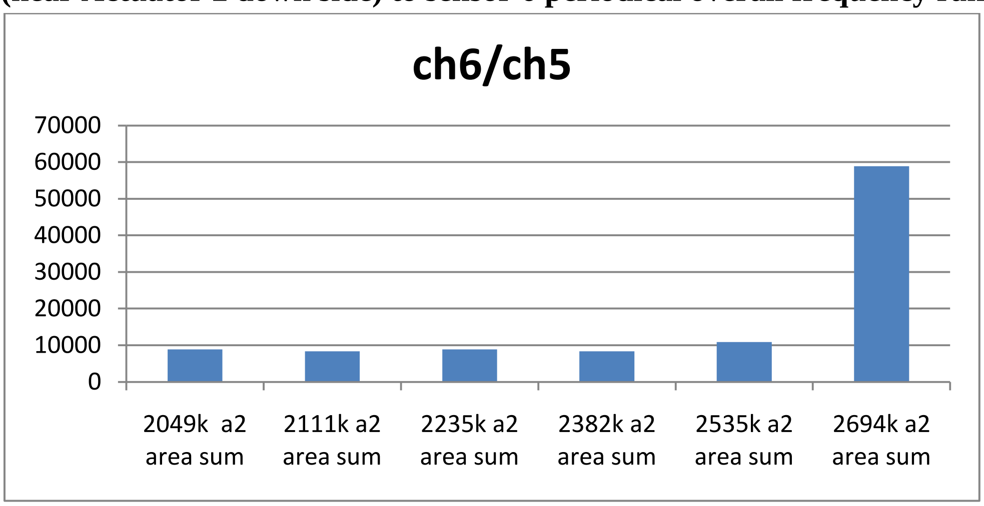


Figure 20 Sensor Blade PZT System FRF (averaged) Transmissibility from sensor 5 (near Actuator 2 down side) to sensor 6 periodical overall frequency range 1-5000 Hz



Explanation of PZT CX-100.TX-100 and BSDS data:

The previously reported CX-100 and TX-100 and BSDS shows that

The PZT is useful for indicating flaw development which affects blade stiffness. It is important that the PZT Actuator and sensors reside on the structural members which experience the stiffness changes. In the case of the TX-100 failure occurs near mid span and the sensors were near the root, this was reflected in limited early failure indications from the PZT system.

Explanation of PZT Sensor Blade Results:
The manufactured deflect does cause surface cracking very early noticed at 25K load cycles with repeated flexing near sensor 3; since the defect was already present the FRF of sensor 1 to sensor 3 does not show a dramatic change. Output voltage amplitudes from sensor 3 were unusually large indicative of the high strain but with the supporting structures of the blade reacting the loads.

However The PZT Graphs do indicate especially on **Figure 18** the FRF between the input sensor 1(near actuator 1) and sensor3 in particular, starting at 1300K load cycles, a change in stiffness which is progressive shows up as higher modes, this is likely a Internal progressive cracking, but without blade cut-up and analysis this cannot be verified.
Final failure is indicated in sudden and dramatic increases in the FRF modes right before total failure Shown by **Figure 20** on the FRF between sensor 5 (near actuator 2) and sensor 6. The large down side crack likely progressed through the shear web and by suddenly showing as a large crack on the down side confirms the final failure mode.

Figures 13-16 provide information report in frequency bins which provide more information. Generally, the lower ranges are less useful as the higher frequencies reflect more localized modes and more sensitive to cracks and void development information. The simplified graphs of **Figures 17-20** which are for the whole frequency range of 1-5000 Hz are still effective as predictors of failure.

Conclusion:
The NASA PZT Heath Monitoring technology has been demonstrated as a predictor of serious flaw development which is a precursor for final failure in the Fatigue tests for the CX-100, TX-100 BSDS and Sensor Blade experimental 9 Meter designs. The system should be integrated as an independent system on operational Field turbines. Ideality to accomplish this the system will require packaging to provide a compact footprint along with remote wireless data handling. The system could be located in the hub of a rotating wind turbine with the sensors/actuators periodically sampled from the 3 blades.
The data could be analyzed with software at the hub computer with the compact data set sent over the internet a low rate using a cellular data system. This system would be non interfering to the turbine controls and provide a series flaw warning prior to catastrophic failure allowing economically scheduled just in time maintenance or replacement of the faulty blade.

Acknowledgments

The author would like to acknowledge and thank the U.S. Department of Energy for its support of blade sensor development programs. We would also like to acknowledge Scott Hughes, Jeroen van Dam and Mike Jenks at the NREL/NWTC blade testing facility for their great help in collection of data and running the project; Mark A. Rumsey of Sandia National Laboratories‡, Albuquerque, NM for His assistance in project management lending computer resources, technical cordination and all others of the Wind Energy Department of Sandia National Laboratories who assisted in installing sensors and providing background for the joint effort with NASA.

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[1] **Evaluation of NASA PZT Sensor/Actuator for Structural Health Monitoring of a Wind Turbine Blade _**
Jose R. Zayas and Joshua Paquette_
Sandia National Laboratories1, Albuquerque, NM 87185-070
Rudolph J. Werlink *NASA KSC, FL 32899* 45th AIAA Aerospace Sciences Meeting and Exhibit
8 - 11 January 2007, Reno, Nevada

[2] **Experimental Results of Structural Health Monitoring of Wind Turbine Blades**
Mark A. Rumsey and Joshua Paquette†
Sandia National Laboratories‡, Albuquerque, NM 87185
Jonathan R. White *Purdue University, West Lafayette, IN 47907-2031*
Rudolph J. Werlink *NASA, Kennedy Space Center, FL 32899*
Alan G. Beattie *Physical Acoustics Corporation, Princeton Junction, NJ 08550*
Corey W. Pitchford *Virginia Polytechnic Institute and State University, Blacksburg, VA 24061*
Jeroen van Dam *National Renewable Energy Laboratory, Golden, CO 80401*
46th AIAA Aerospace Sciences Meeting and Exhibit
8 - 11 January 2008, Reno, Nevada

Structural Health Monitoring of Wind Turbine Blades
Mark A. Rumsey and Joshua A. Paquette
Sandia National Laboratories, Albuquerque, NM 87185
Published 7 April 2008 | Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring SPIE Conference

[3] **Fatigue Test of an Experimental BSDS Wind Turbine Blade PZT Active Vibration Heath monitoring and Acoustic Emission Results** Rudy Werlink PE MS NASA Kennedy Space Center
Dr. Alan G Beattie Physical Acoustics Corporation
The 7th International Workshop on Structural Health Monitoring - 2009 Stanford University Stanford, CA USA Sept. 9-11, 2009

[4] Figures and Description from
2008 Wind Turbine Blade Workshop
Sensor Projects at Sandia National Laboratories
Mark A. Rumsey marumse@sandia.gov
Wind Energy Technology Department
Sandia National Laboratories
Albuquerque, NM
May 14, 2008

[5] Ibid

[6] Fatigue Testing Setup Description from final report
Acoustic Emission Monitoring of the Sandia Sensor Blade Fatigue Test
Dr. Alan G Beattie

[7] Figures from Mark A. Rumsey
Wind Energy Technology Department
Sandia National Laboratories
Albuquerque, NM

[8] **Laser Shearography of the "Sensor" Wind Turbine Blade**
At the National Renewable Energy Laboratory,
National Wind Test Center (NWTC)
John W. Newman, President
Laser Technology, Inc.
John Lindberg, PE
Program Manager – NDE Innovation,
Electric Power Research Institute (EPRI)

[9] Figures from Mark A. Rumsey
Wind Energy Technology Department
Sandia National Laboratories
Albuquerque, NM